Loran ASF Variations as a Function of Altitude

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In 2001, the Volpe National Transportation Systems Center completed an evaluation of GPS vulnerabilities and the potential impacts to transportation systems in the United States. One of the recommendations of this study was for the operation of backup system(s) to GPS; Loran-C was identified as one possible backup system. The Federal Aviation Administration (FAA) has been leading a team consisting of members from industry, government, and academia to evaluate the future of Loran-C in the United States. In a recently completed Navigation Transition Study, the FAA concluded that Loran-C, as an independent radionavigation system, is theoretically the best backup for the Global Positioning System (GPS). However, in order for Loran-C to be considered a viable back-up system to GPS, it must be able to meet the requirements for non-precision approaches (NPA's) for the aviation community, and the Harbor Entrance and Approach (HEA) requirements for the maritime community.

A significant factor limiting the accuracy of a Loran system is the spatial and temporal variation in the times of arrival (TOAs) observed by the receiver. A significant portion of these variations is due to the signals propagating over paths of varying conductivity; these TOA corrections which compensate for propagating over non-seawater paths are called additional secondary factors (ASFs). Hence, a key component in evaluating the utility of Loran as a GPS backup is a better understanding of ASFs and a key goal is deciding how to mitigate the effects of ASFs to achieve more accurate Loran-C positions while ensuring that the possibility of providing hazardous and misleading information (HMI) will be no greater than 1x10-7.

Another aspect of spatial variation is the change in ASF due to altitude. To enable Loran to meet RNP 0.3 for airport approaches it is important to know the magnitude of this variation over the maximum 4000 ft range of altitude between the final approach point and the tarmac. This range of variation needs to be bounded and accounted for in the error budget. There has been a limited amount of discussion and investigation of this effect in the literature. We have observed and investigated this effect over the past two years, but have not fully resolved it. Additional testing using an airship and better ASF measuring equipment has been recently conducted in order to more accurately quantify this effect. This paper summarizes the effects seen previously, describes the equipment and procedure for the new testing to quantify this variation, details the proposed airship testing, and provides a review of previous research and a model for predicting the altitude variations.

Introduction

Given the ubiquity and quality of service available from the Global Positioning Service (GPS), one might wonder of what use is a system that has been operational since the 1970's? The answer is that Loran is an excellent backup system for GPS. As discussed in many sources, such as the Volpe vulnerability study [1], GPS is vulnerable to both intentional and unintentional

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jamming. Since Loran is a totally different system and subject to different failure modes than GPS, it can act as an independent backup system that functions when GPS does not. The Federal Aviation Administration (FAA) observed in its recently completed Navigation and Landing Transition Study [2] that Loran-C, as an independent radionavigation system, is theoretically the best backup for GPS; however, this study also observed that Loran-C's potential benefits hinge upon the level of position accuracy actually realized (as measured by the 2 drms error radius). For aviation applications this is the ability to support non-precision approach (NPA) at a Required Navigation Performance (RNP) of 0.3 which equates to a 2 drms position error of 309 meters; for marine applications this is the ability to support Harbor Entrance and Approach (HEA) with 8-20 meters of accuracy.

A significant factor limiting the accuracy of a Loran system is the spatial and temporal variation in the times of arrival (TOAs) observed by the receiver. A significant portion of these variations is due to the signals propagating over paths of varying conductivity; the TOA corrections which compensate for propagating over non-seawater paths are called additional secondary factors (ASFs). Hence, a key component in evaluating the utility of Loran as a GPS backup is a better understanding of ASFs and a key goal is deciding how to mitigate the effects of ASFs to achieve more accurate Loran-C positions while ensuring that the possibility of providing hazardous and misleading information (HMI) will be no greater than $1x10^{-7}$. For an aviation receiver, the approach under study to mitigate propagation issues is to use a single set of ASF values (one for each Loran tower) for a given airport. If the local ASF variations are too large to meet the accuracy targets with a single set of ASF values, then additional sets will be used with the user's receiver interpolating between ASF values. This approach is described in detail in [3] and in our companion paper at this conference [4].

In order for this approach to be valid, the range of variation of the ASFs along the airport approaches must be known as the error model for certification of an airport is dependent upon the variations and error sources being bounded. Previous efforts have focused on the spatial and temporal variations; here we focus on another source of variation for aviation users, ASF variation with altitude. There has been considerable debate over the past year over whether this possible altitude effect on ASFs is in fact a problem or not. However, in recent months opinions seem to have gelled, that in fact this is an issue that needs to be resolved. The Airport ASF Methodology [4] that the ASF Working Group has been developing and validating for the FAA relies on bounding the total ASF "error" where by "error" we mean the difference from the actual ASF at a given location along the approach path to the ASF value being used by the receiver in the position solution. Our companion paper [4] explains this Methodology in detail, and focuses on the effect of the variation in the actual ASFs from the value being used by the receiver. Spatial variation along the ground is well-understood and accepted. However, aircraft start their approach at up to 4000 ft AGL. If the altitude effect increases the ASF variation sufficiently then the position domain bound of 120 m to meet RNP 0.3 will be exceeded. This additional ASF variation needs to be considered when determining whether a single set of ASF values is sufficient for a given airport or airport approach or whether, instead, multiple sets will be needed. For example, in Figure 1 the impact of 200 nsec of additional ASF error due to altitude is shown for Runway 11 at Portland International airport (PWM). Here the additional error pushes the 95% error bound above 120 m at 10NM from the runway end.

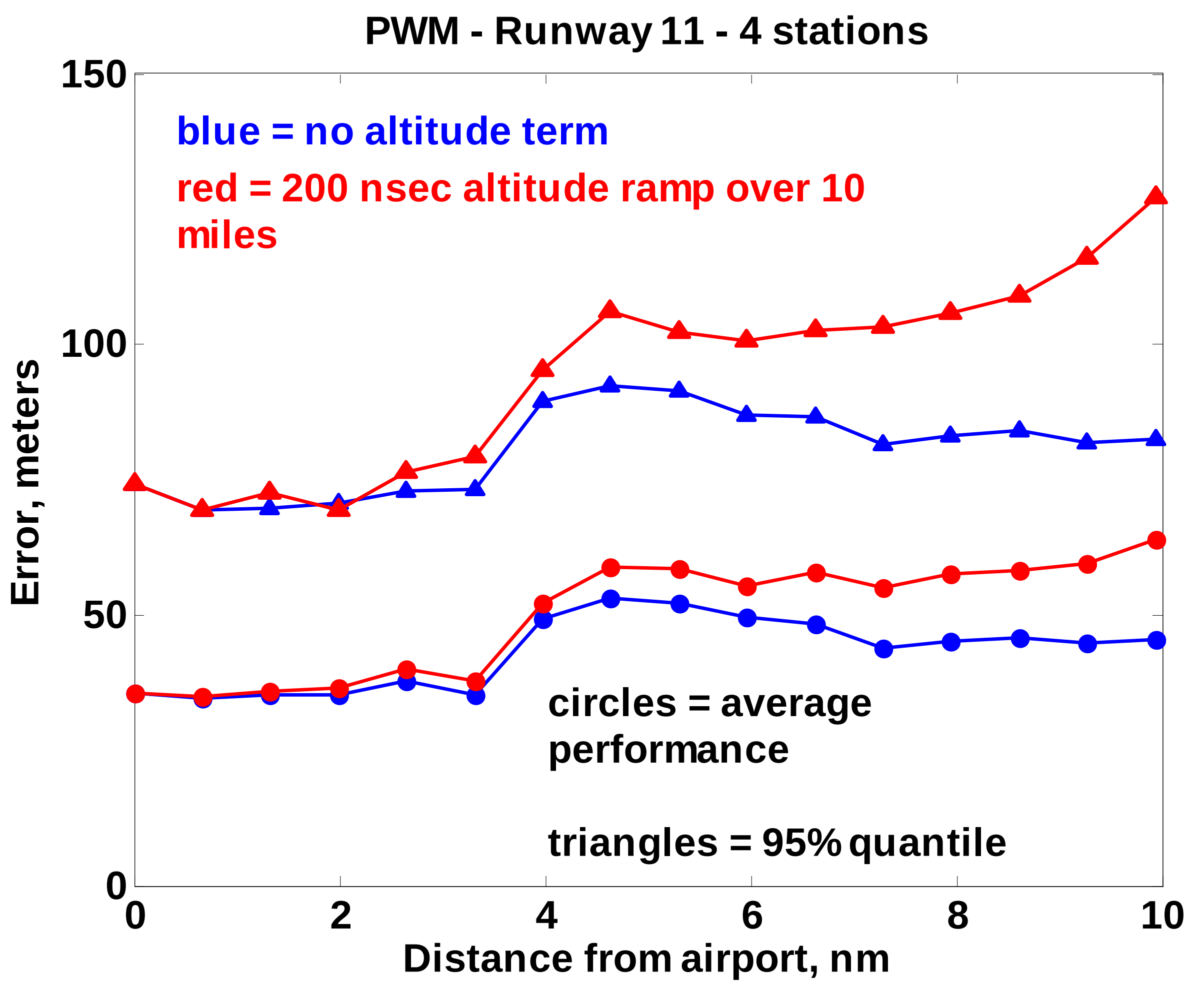

Figure 1: Altitude Impact on Position Error.

Altitude Test History

This variation in the ASF as a function of altitude was first noticed in our data collection and analysis of spatial ASF variations 2-3 years ago. In order to quantify this effect, further study was needed. In order to look at the variation as a function of altitude, the ideal data collection would be to do measurements in a slow vertical profile. This was not possible with the data collection platform available at that time (the FAA's Convair 580) so an alternative method was devised. The typical flight plan was to fly as slowly as possible back and forth between two points, flying each direction at the given altitude prior to moving up to the next altitude. The goal was to maintain the same ground track so that any variations in the ASFs between successive passes would be due to altitude only. Only two reciprocal headings were used so that only passes in the same direction could be compared to eliminate the directional effect of the H-field antenna.

Figure 2: Interior of Convair looking forward; CGA DDC receiver in rack.

The first altitude test was conducted in January 2003 in conjunction with other flight tests with the FAATC. Details of this flight testing was discussed in [5]. Unfortunately, the receiver was set to adjust the internal oscillator according to the strongest Loran station so that the TOA measurements were not consistent. So, although the test showed that the USCGA DDC receiver could be used in the aircraft (Figure 2), it also showed that the receiver would need to be stabilized with an external clock signal. The altitude test was repeated in May 2003 using the DDC receiver stabilized with an external 10MHz reference from a NovAtel GPS receiver. A new version of the receiver was used which allowed each 1 second of data samples to be time-tagged to UTC. This allowed real TOA measurements to be made, independent of the receiver's clock. The flight path is shown in Figure 3 with the altitude test segments being the straight segments running SW-NE. The flight included passes at altitudes from 2500 to 6500 ft. and this test indicated some differences in ASF due to altitude of from 100-400 nsec.

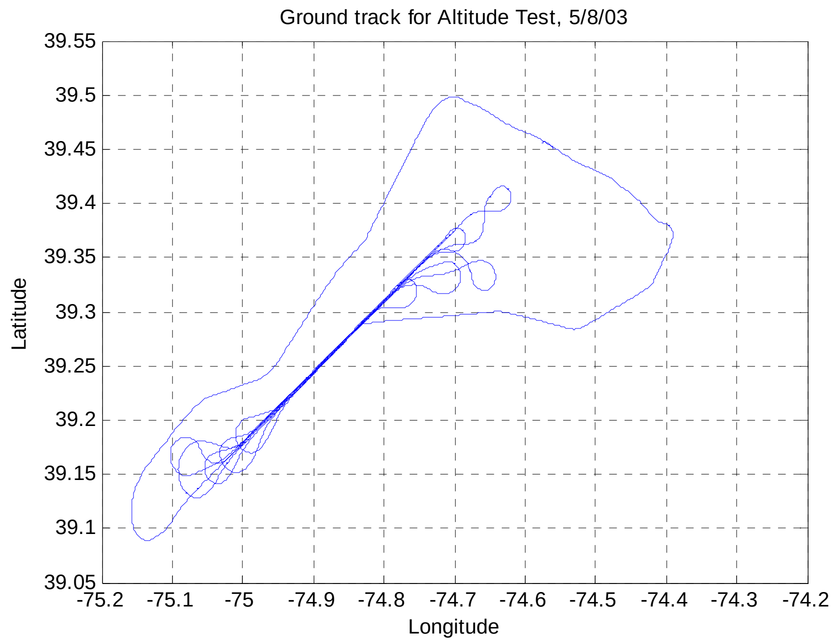

Figure 3: Flight ground track for altitude test in May 2003.

During the Summer of 2003 a series of flight tests and ground measurements were conducted at various airports in the United States [6]. During the testing in the Point Pinos, CA area an altitude test was included. The Convair 580 flew back and forth over the same ground track at various altitudes with the altitude segments flown primarily North-South. The two closest stations were Searchlight and Fallon, NV (see Figure 4). Two sets of plots were done, one for each direction due to the directional error in the H-field antenna. In the case of Searchlight, there are some fairly large differences between 4500 and 9000 ft while in the case of Fallon, the differences were much less. This test was somewhat inconclusive and highlighted a need to improve the ASF measurement capability on the aircraft. ASF measurements on an aircraft are notoriously difficult and are not highly precise due to the high noise environment and high dynamics of the aircraft.

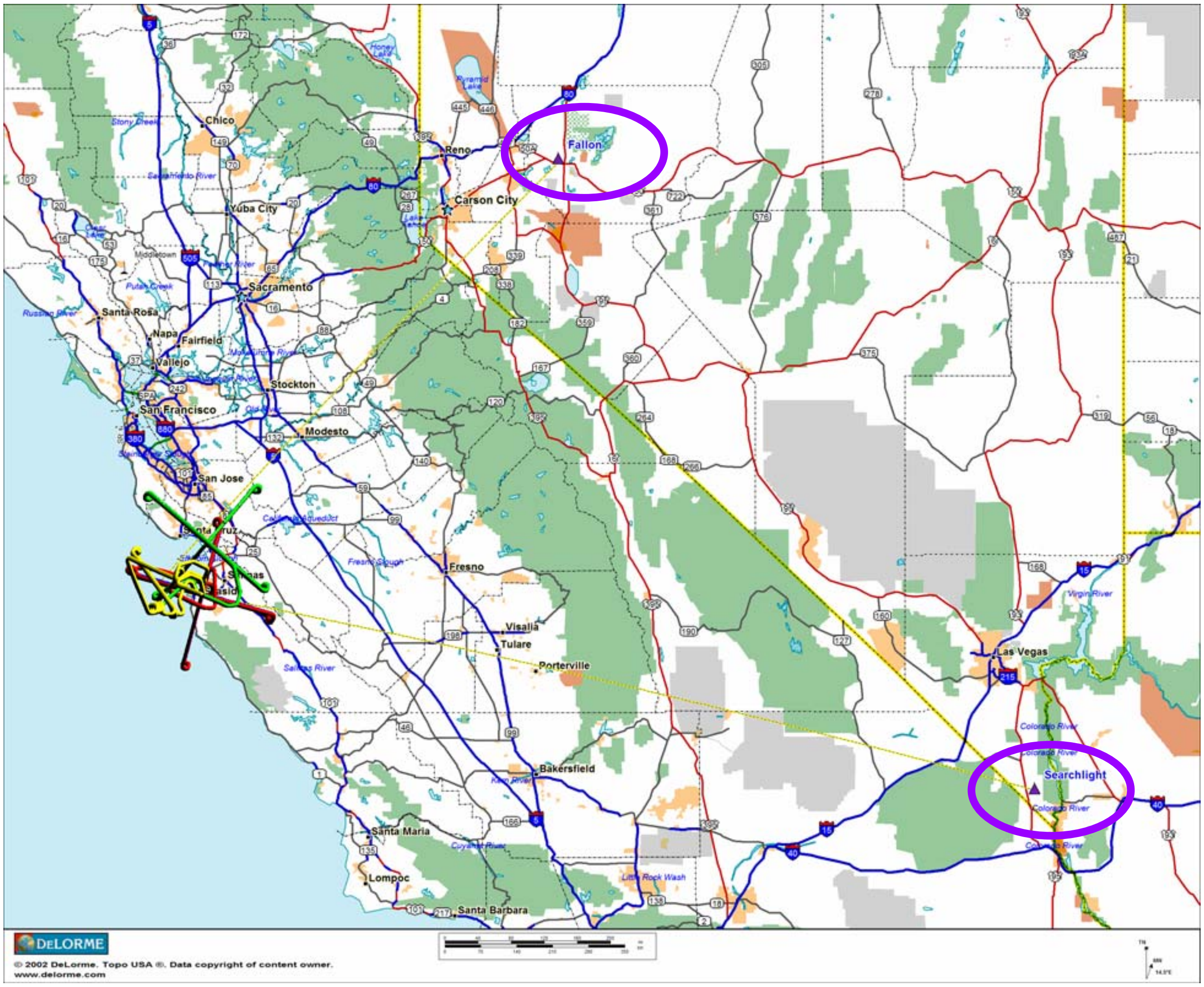

Figure 4: Flight paths for altitude testing near Point Pinos, CA. Altitude test is part of the yellow flight track. Loran Stations Searchlight and Fallon are circled in purple.

The most recent and most accurate aircraft altitude test was conducted in October 2004 using the SatMate ASF measurement system [7] on the Convair. The test was conducted in a similar manner to the previous (repeating ground tracks at various altitudes) in the vicinity of the FAA Technical Center in Atlantic City, NJ. The ground tracks for the 5 southbound legs (altitudes of 300-3000 m) are shown in Figure 5 with the directions to the two strongest Loran stations (Seneca and Nantucket) shown. The accuracy of ASF results was somewhat reduced due to the fact that the SatMate receiver did not use a stabilized clock reference (the modified SatMate was still on order) and thus the results were somewhat corrupted by Doppler. An estimate of the receiver clock was made with each data sample so that the clock could be removed; however, this method has been seen to be less accurate in our work than using a stable external clock. To alleviate this and the error from the directionality of the H-field antenna, results from only one direction are shown. The ASFs have been recalculated from the TOAs in a post-processing mode taking into account receiver averaging delay. Since the ASF is calculated using the GPS position as the ground truth, and the receiver TOA data is averaged, the true position corresponding to the TOAs must be estimated.

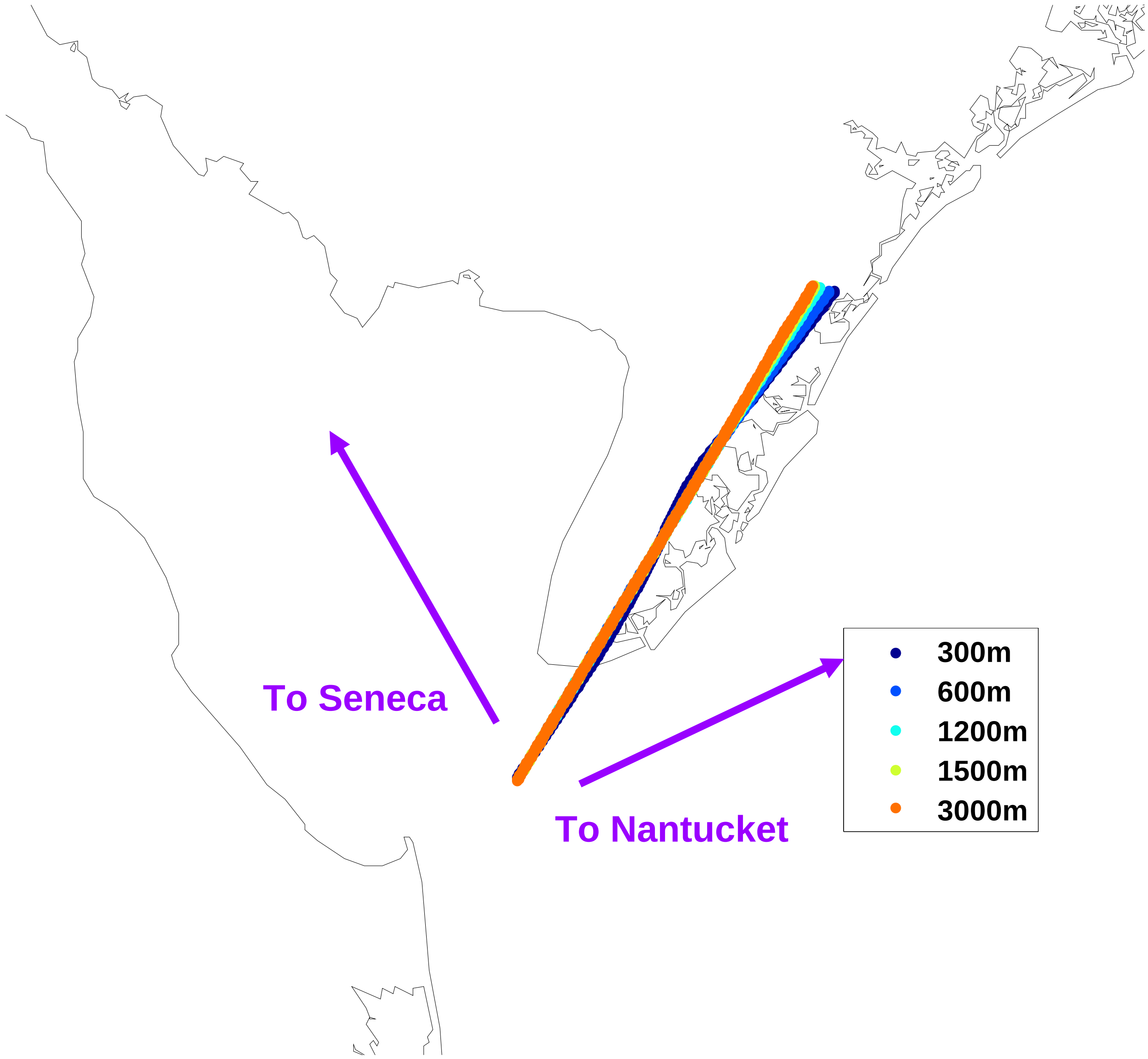

Figure 5: Ground tracks for altitude test, October 2004.

Results from Nantucket (Figure 6) and Seneca (Figure 7) are shown. These should have about the same Doppler error as the angles from the Stations to the track are about the same (in opposite directions). The altitude ASF variation for Seneca is much greater than that for Nantucket which makes sense as the path from Nantucket is almost entirely seawater. The largest altitude effect should be seen on paths crossing the lowest conductivity ground which is the case for Seneca. Also, the largest altitude effect for Seneca is seen at the northern end of the legs where the path is all over land as compared to the southern end where the path covers part of the Delaware Bay. These results will be put in context and shown to be in agreement with theory later in the paper.

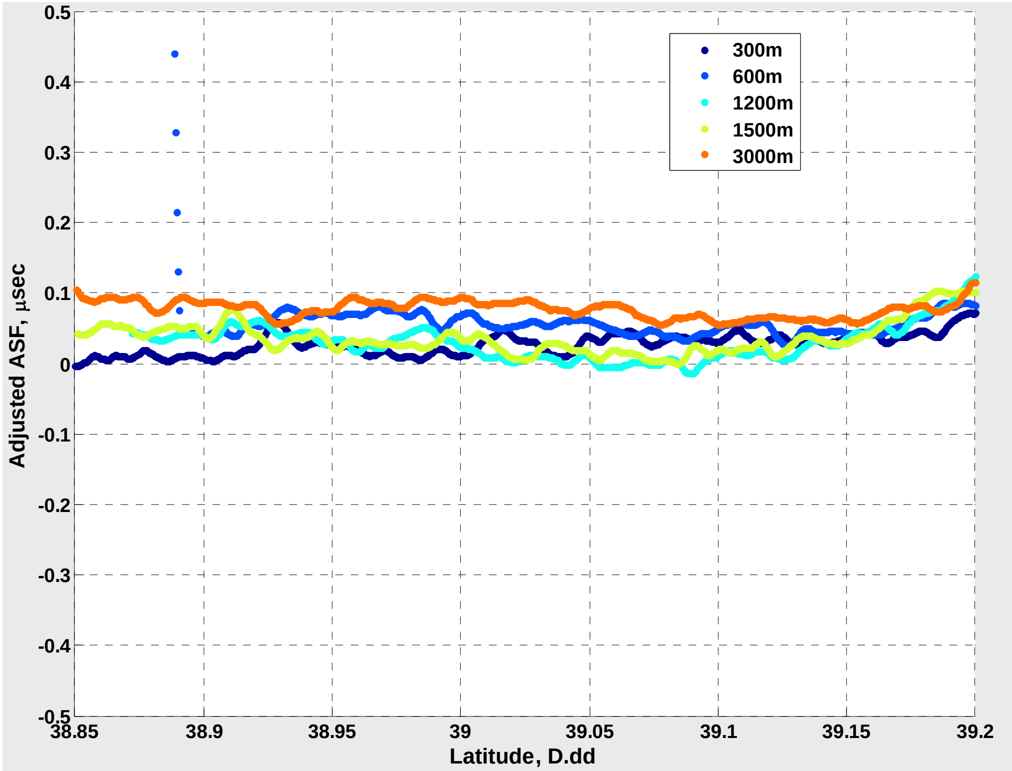

Figure 6: ASF vs. Latitude for various altitudes, Nantucket, southbound.

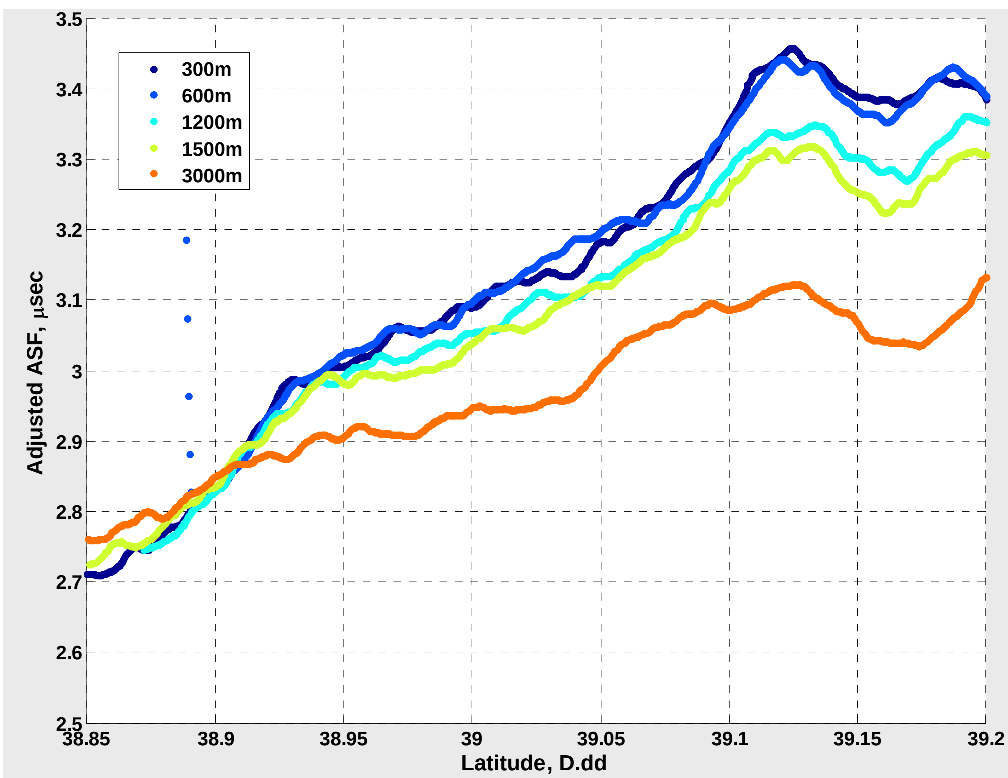

Figure 7: ASF vs. Latitude for various altitudes, Seneca, southbound.

Summary of Previous Research

In order to better understand this altitude variation, we turned to the historical record to see what previous researchers had discovered. J. R. Johler included in his 1971 report [8] information on altitude effects and in this reports states "…it is further concluded that the altitude correction must be determined from theory or measured in case of severe perturbations due to unusual local anomalies." Burch, Doherty, and Johler also address altitude variances in their Wild Goose Assoc. paper in 1975 and include a chart showing the predicted phase variations at different altitudes (Figure 8). Johler includes a different chart of predicted phase variations at different altitudes in his 1976 AGARD paper (Figure 9). In this paper Johler writes:

> It is further concluded that such propagation anomalies are significant not only on the ground in the immediate vicinity of the anomaly, but also aloft and at great distance from the anomaly. It is also concluded that the type of antenna used by aircraft navigating on Loran must be considered as to its effect on the secondary phase correction at shorter distance from the transmitter. It is also noted that the type of antenna is significant to even greater distance as the altitude of the aircraft is increased.[9]

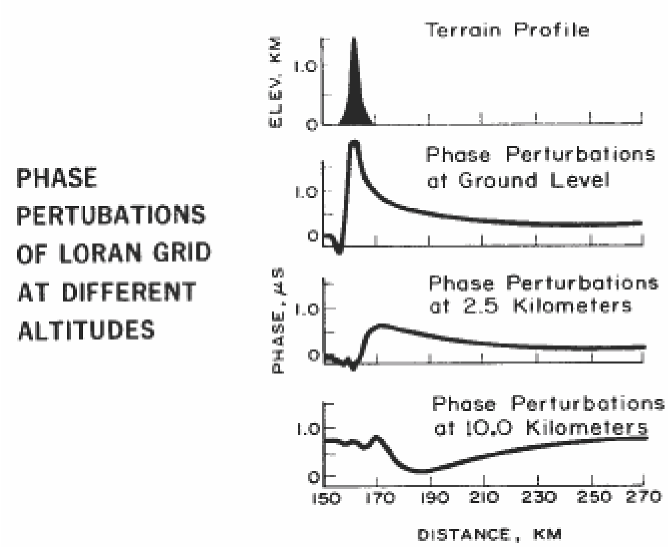

Figure 3. Predicted phase variations at three altitudes.

Figure 8: Figure reprinted from [10].

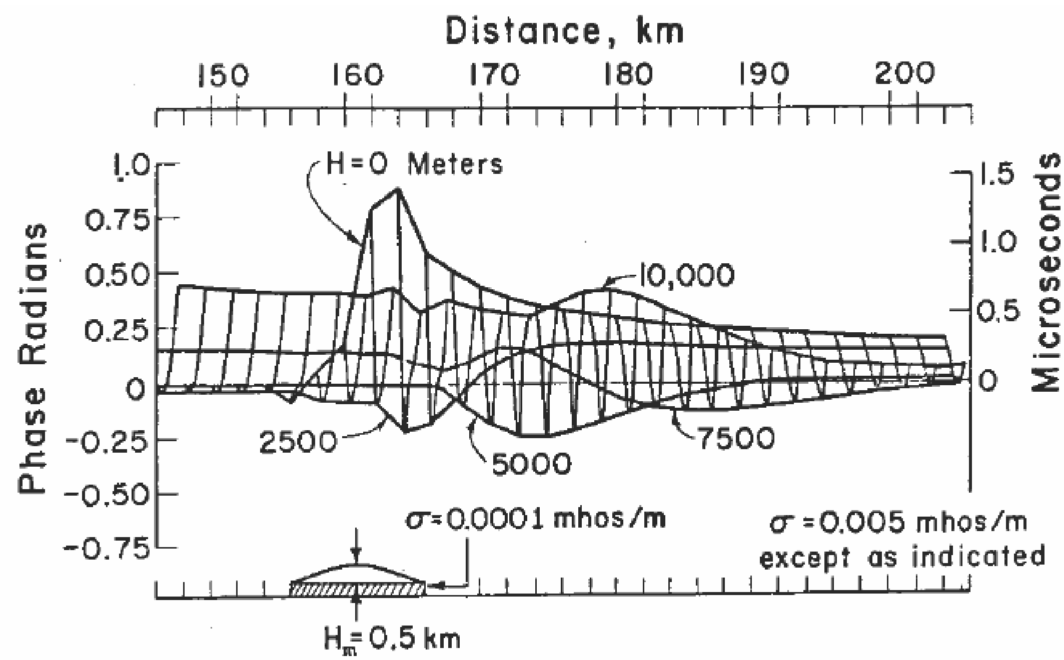

Figure 9: Figure reprinted from [9].

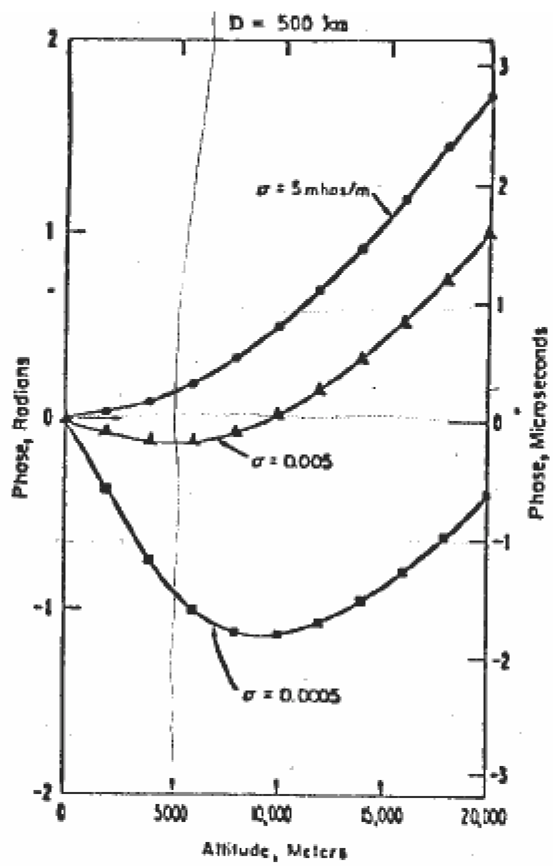

Figure 10: Figure reprinted from [11].

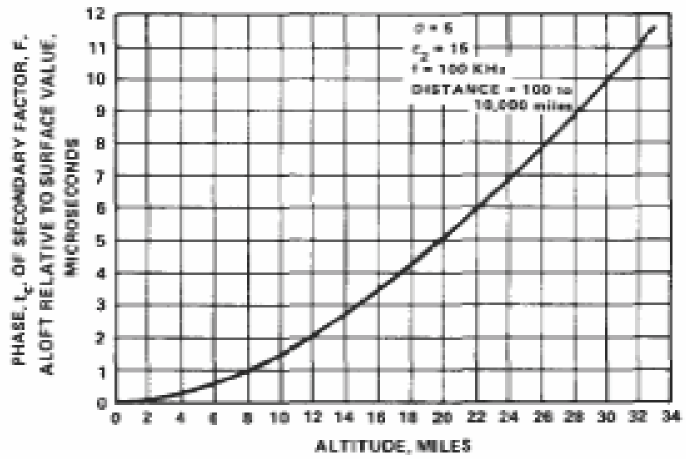

Fig. 6—Variation of phase of the secondary factor with altitude.

Figure 11: Figure reprinted from [12].

Curves of phase change with altitude have also been published by O'Halloran and Natarajan (Figure 10) and Samaddar (Figure 11).

Several authors have also looked at the impact of meteorological effects on the temporal change in ASF as a function of altitude. Doherty and Johler investigated the weather effects on vertical lapse rate and the refractive index in 1976 [13]. Gressang and Horowitz in 1978 examined the impact of the refractive index of the atmosphere at the surface and the lapse rate or rate of change of the refractive index with altitude above the surface [14]. Doherty, et al in 1979 assert that the most important parameter is the atmospheric vertical lapse factor, alpha [15]. And finally Comparato and MacKenzie showed that temporal fluctuations due to the vertical lapse rate yielded phase changes with altitude of up to 400 nsec [16].

Physical Theory

O'Halloran's and Sammadar's curves were derived from complex formulas for the propagation of waves over ground. We decided to examine the physical paths that the signals take to attempt to put the variations into context. We have looked at two first-order effects associated with the path the signal takes from a Loran station to a receiver at altitude. First is the extra path length of the straight-line Line-of Sight (LOS) path between the horizon and the receiver versus the surface path from the horizon to the ground point (point on the ground immediately below the receiver at altitude). The LOS path is always longer than the path along the curved surface; however the receiver in its calculations always assumes the surface path. The second is the reduced Secondary Factor (SF) and ASF accumulation along the LOS path as this path is through the atmosphere not over the ground and thus is only subject to the Primary Factor (PF) not SF or ASF. There are two cases to consider: a) the tower over-the-horizon of the receiver, and b) the receiver close to the tower.

Over-the-Horizon Case

The first case to consider (diagrammed in Figure 12) is the case of the receiver (labeled airship) sufficiently far from the Loran tower that it is always over-the-horizon, regardless of altitude. In this case the Loran signal propagates as a surface wave over the ground (accumulating ASF as a function of conductivity and terrain) until it reaches the horizon point. This horizon point is, of course, a function of the altitude (labeled *h*) of the receiver above ground. The signal then propagates through space along the straight-line LOS path. This distance is:

$$D_{LOS} = \sqrt{(h + r_e)^2 - r_e^{\,2}}, \quad r_e = \text{earth radius}$$

The receiver assumes that the signal travels along the surface path to the ground point:

$$D_{surface} = r_e \cdot \arctan\left(\frac{D_{LOS}}{r_e}\right)$$

The extra path length that the signal travels is $D_{LOS} - D_{surface}$. This distance can be converted into time by dividing by the speed of light through the atmosphere (PF). This extra path length is plotted versus altitude in Figure 13. At the maximum altitude for runway approaches of 4000 ft, this difference is 55 nsec.

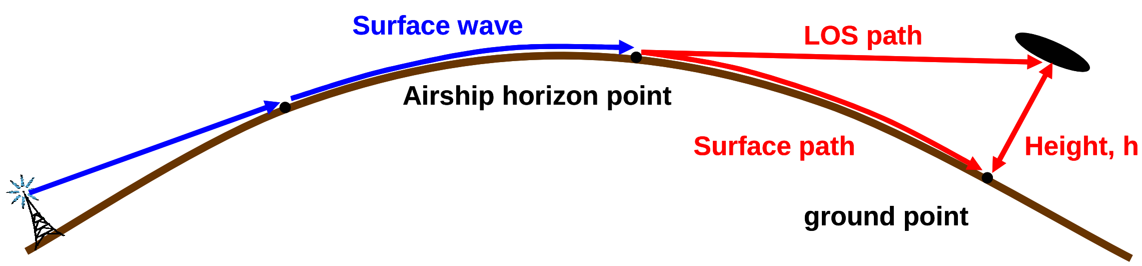

Figure 12: Tower over-the-horizon. Path length calculations.

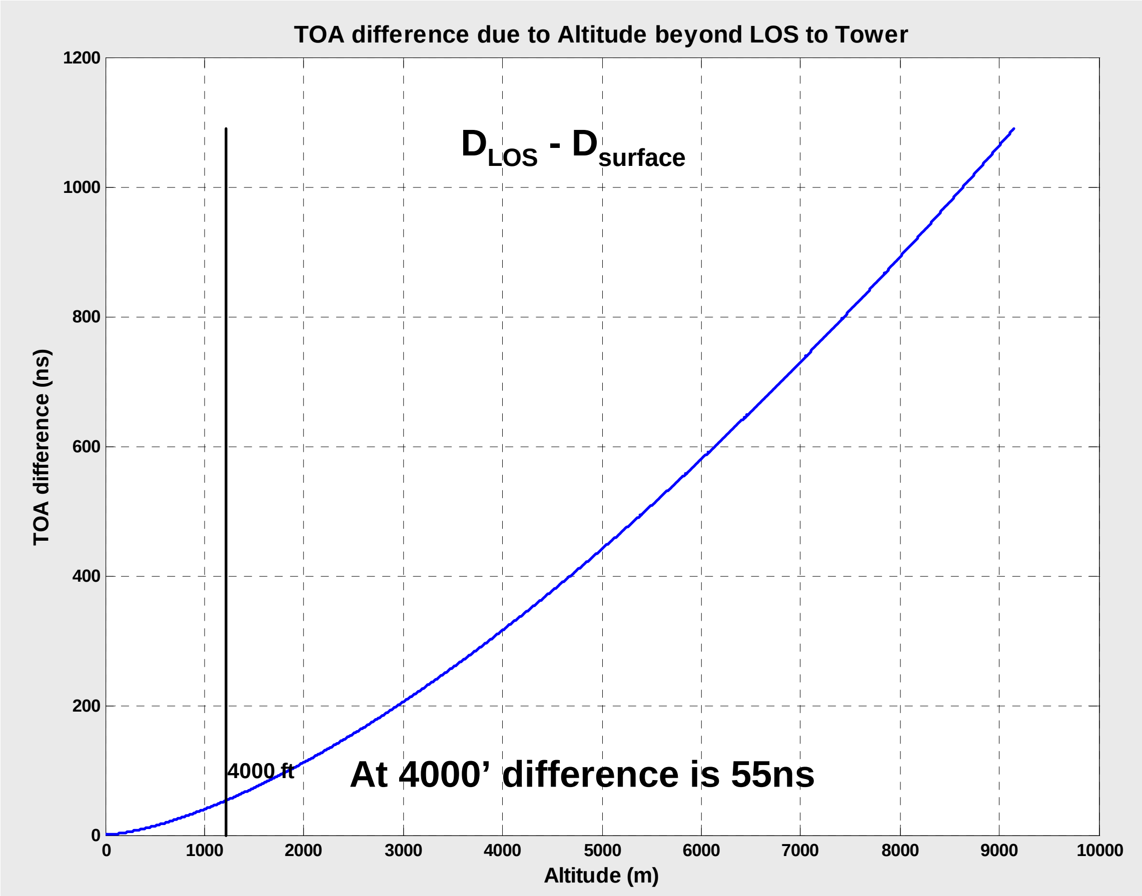

Figure 13: TOA difference (nsec) versus altitude (m) due to LOS path.

The second effect to consider is the reduced SF and ASF. Since D_{LOS} is though the atmosphere there is no accumulated SF or ASF along this path as opposed to along the ground, $D_{surface}$. In order to examine the magnitude of this effect, ASF predictions were calculated using the BALOR software for a specific test case area. The area near Atlantic City used in the October 2004 test (Figure 5) was selected so that the theoretical results could be compared to the measurements. Four initial starting points were selected along the ground tracks. For each ground point (1-4), the horizon points towards Seneca and Nantucket for various altitudes from 300-3000 m were calculated. These are shown in Figure 14, blue circles for Nantucket and red circles for Seneca. BALOR was used to calculate the ASF value to each horizon point (ASF_{HP}) and each ground point (ASF_{GP}). The expected TOA for each altitude was then calculated as:

$$TOA_{expected}(h) = predTOA_{HP}(PF\ \&\ SF) + ASF_{HP} + {D_{LOS}(h)}/{c_{PF}}\ ,\ c_{PF} = \frac{c}{\eta}$$

The expected TOA measured at the surface would be:

$$TOA_{expected}(surface) = predTOA_{GP}(PF\ \&\ SF) + ASF_{GP}$$

And thus, the change in expected TOA (or equivalently the change in ASF) with altitude would be:

$$\Delta ASF = TOA_{expected}(h) - TOA_{expected}(surface)$$

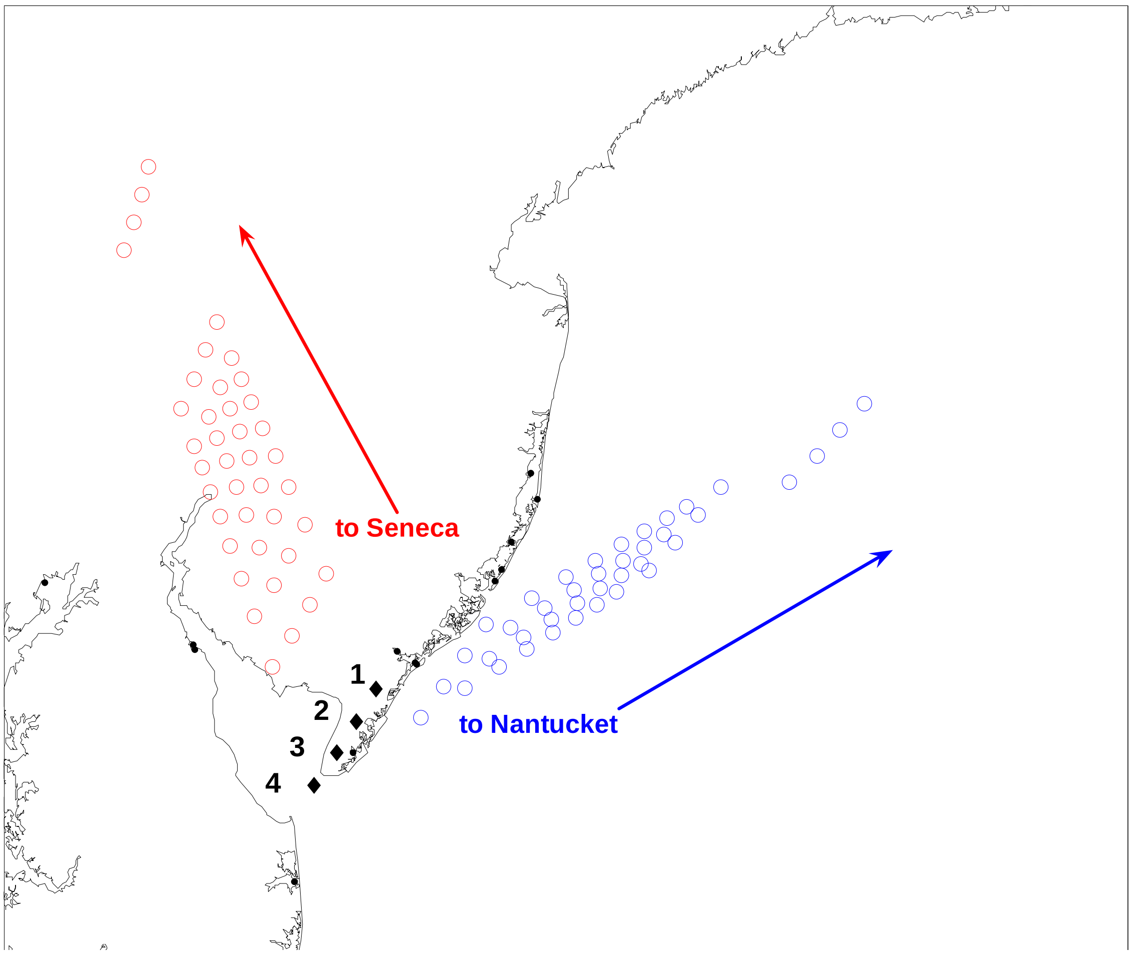

Figure 14: Ground points and calculated horizon points for various altitudes.

This ASF difference (change relative to the ground ASF value) as a function of altitude is plotted for Nantucket (Figure 15) and Seneca (Figure 16). The ASF difference versus altitude for the range shown is very small for Nantucket (~100ns), which makes sense as the horizon points from the first altitude step are in the ocean, and the path to Nantucket is all-seawater, thus there is very little ASF to be reduced with altitude. The initial drop with altitude is due to the decreased SF accumulation, and then the increase is due to the extra path length which is greater and greater with altitude. The difference between the individual curves is due to the BALOR predicted ASF value for the points 1-4, which may be in error as BALOR has not been validated.

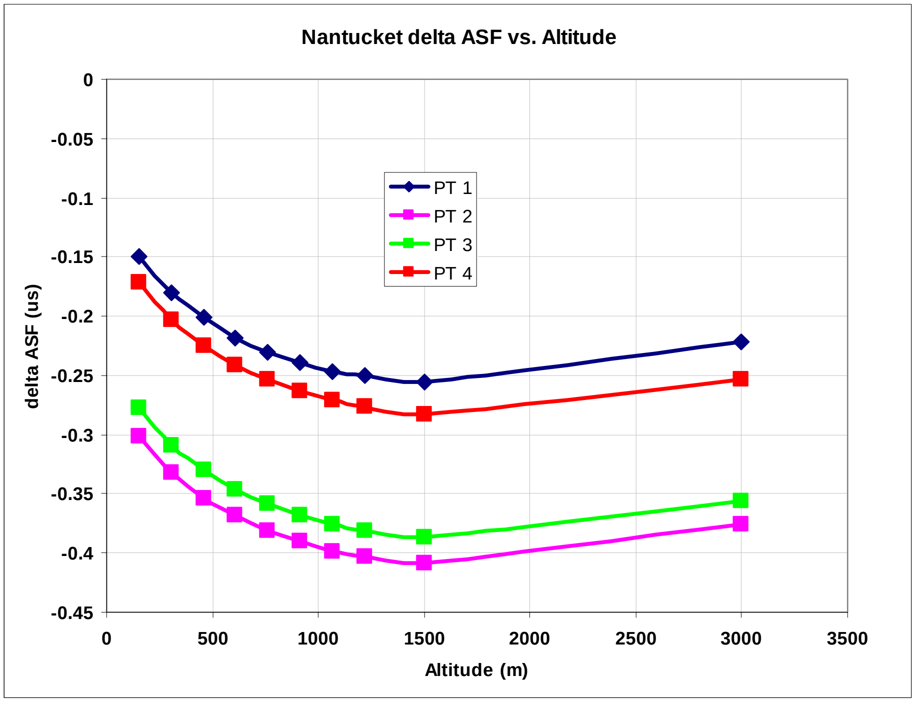

Figure 15: Nantucket delta ASF.

In the Seneca curves, there is a much greater change (500 nsec) as the path to Seneca is an all-land path and thus there is a much larger ASF value to be reduced with altitude. The effect of the longer path length does not dominate until much higher altitudes. Again, the initial values are a function of BALOR, which has not been validated.

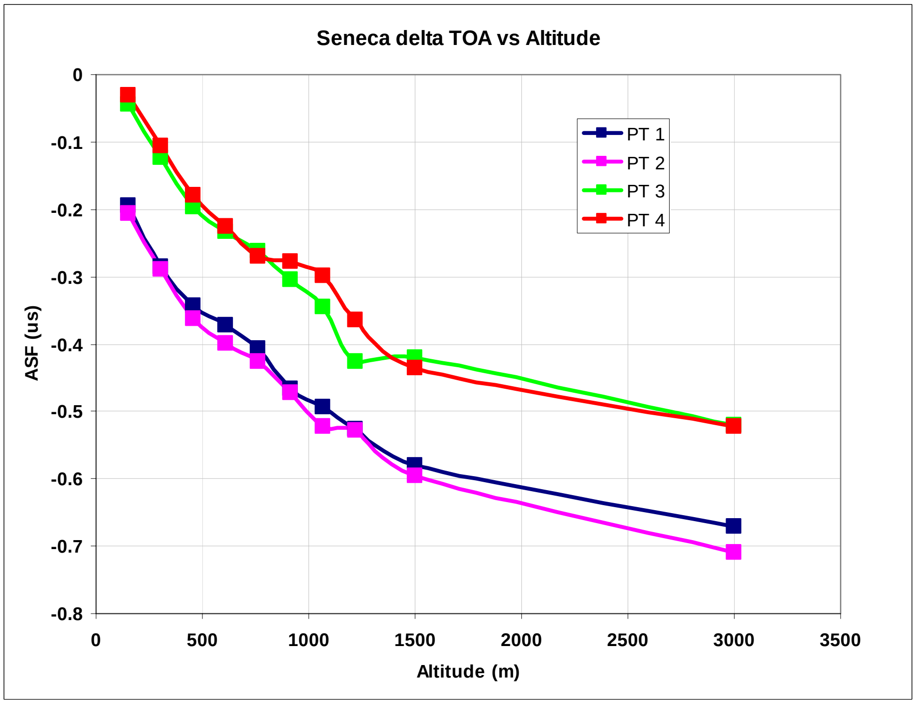

Figure 16: Seneca delta ASF.

Both of these predicted curves compare to the measured data from October 2004 (Figure 6 and Figure 7) in that for Nantucket there is very little change and for Seneca there is a much greater change with altitude. The data from October 2004 was collected without a stabilized receiver however, and suffered from 50-100 nsec of noise, due to the aircraft, making precise measurements impossible.

Within LOS of Tower Case

The second case to consider is if the receiver is operating within Line-of-Sight (LOS) of the transmitter. The geometry is shown in Figure 17. This problem is parameterized in 2 variables, the distance d of the receiver from the tower along the ground, and the height *h*, of the receiver above the ground. For each altitude, *h*, considered, the distance, *d*, is allowed to vary from 0 (directly over the tower) to the tower horizon point. The tower horizon point is a function of the receiver height, h, and is found as before:

$$D_{LOS} = \sqrt{(h + r_e)^2 - r_e^{\,2}}, \quad r_e = \text{earth radius and}$$

$$D_{surface} = r_e \cdot \arctan\left(\frac{D_{LOS}}{r_e}\right)$$

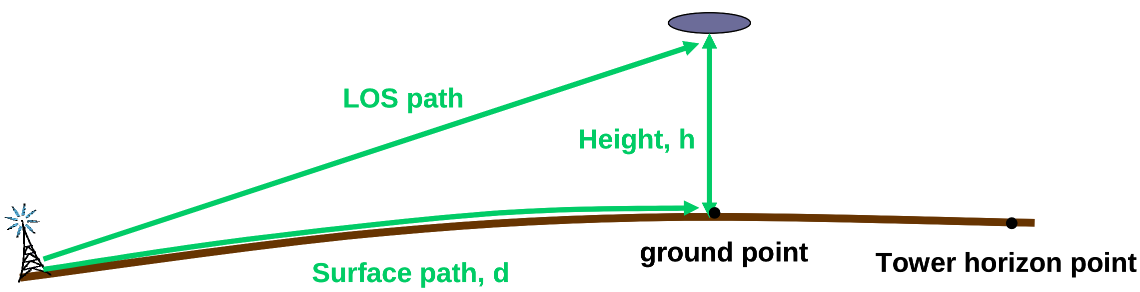

Figure 17: Geometry for LOS case.

The LOS path is a function of both *h* and *d*:

$$D_{LOS} = \sqrt{(h + r_e)^2 + r_e^2 - 2(r_e + h)r_e \cos(\theta)}, \quad \theta = \frac{d}{r_e}$$

$$\Delta Path = D_{LOS} - d$$

The expected TOA for each altitude (*h*) and distance from the tower (*d*) was then calculated as:

$$TOA_{expected}(h,d) = D_{LOS}(h,d)$$

The expected TOA measured at the surface is:

$$TOA_{expected}(0,d) = predTOA_{PF,SF}(d) + ASF(d)$$

And thus, the change in expected TOA (or equivalently the change in ASF) with altitude is:

$$\Delta ASF = TOA_{expected}(h,d) - TOA_{expected}(0,d)$$

Assuming that over these short ground distances the ASF is small and can be neglected, one would expect the largest impact to be the increased distance along the LOS path. This is shown in Figure 18 neglecting ASF and SF. The path length difference is obviously greatest directly over the tower where the ground path distance is 0. As the distance from the tower increases, the path difference decreases and tends towards a constant value. If however, we include the impact of the secondary factor, the results change somewhat. The SF versus distance is plotted in Figure 18 as a dashed red line. As can be seen, the SF tends towards infinity at short distances, so the SF equations may not be valid at close range. The SF decreases and then increases, so that at the longest distances, the SF will dominate. Subtracting off the SF yields the curves shown in Figure 19.

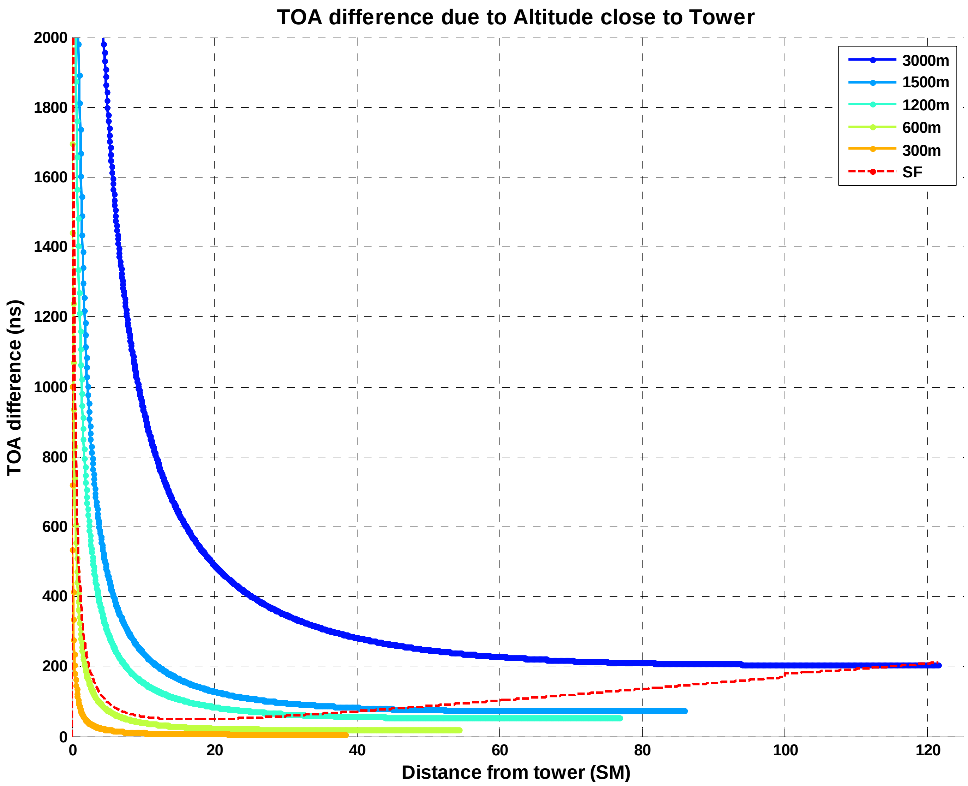

Figure 18: TOA/ASF difference versus altitude and distance from the tower -- neglecting ASF and SF.

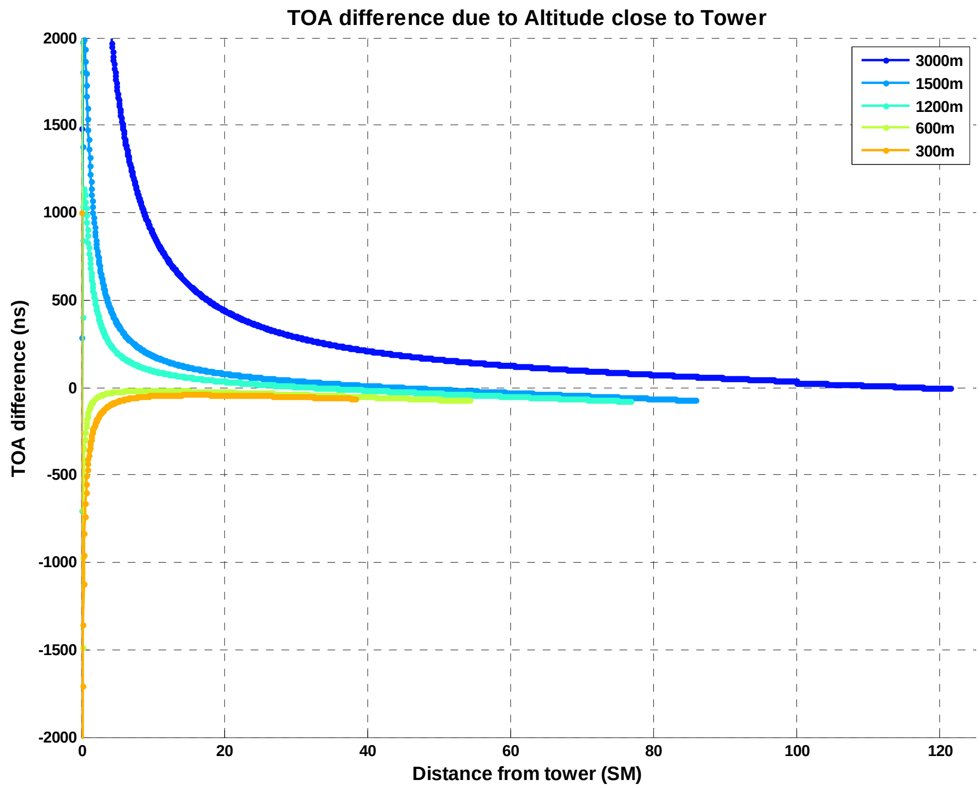

Figure 19: TOA difference after removing the SF.

Both of these cases are somewhat simplistic in that they assume that a wave propagating to a receiver at any height is not affected by the ground at all. This is probably not true for low altitudes, but at least gives a first order approximation to the effects.

Airship Test

Recently, the original concept of doing a slow vertical profile was revived. We had the idea that this might indeed be possible using an airship (such as seen in Figure 20). After some research, and meetings with an airship company, it was determined that this was indeed possible. A procedure and test plan were developed. The goal is to make accurate ASF measurements at static locations at various altitudes. For RNP 0.3, 4000 feet AGL is the maximum altitude of interest (the maximum altitude for starting an airport approach) so the plan is to make both E and H-field antenna measurements at 500 ft increments from 500 to 4000 ft. The plan calls for data to be collected for 30 minutes at each altitude increment so that the results can be averaged yielding a single ASF value for each altitude increment. Differencing the collected data from a static monitor at ground level and correcting for system time errors using TFE data will provide an ASF profile versus altitude. Weather information at the site and along the propagation paths will be collected for archival value.

Figure 20: Fuji airship tethered in Elizabeth City, NC.

A contract was awarded to Airship Management Services Inc. to support two airship tests; one in the New England area and one in Atlantic City, NJ at the FAA Technical Center. The testing was to have taken place first at the FAA Technical Center to resolve any equipment difficulties and then in New England, with both tests completed by the end of September 2005. A series of scheduling difficulties intervened, delaying the tests. The first opportunity ended up being in New England on 22 September 2005. The equipment was installed on the airship at Floyd Bennet Field in Brooklyn and then the airship flew to Sikorski Field in Bridgeport, CT for the test (see Figure 21, Figure 22, and Figure 23). Unfortunately, after takeoff, a piece of equipment (Rb 10MHz reference) failed, causing the data collection to be invalid. The second test at FAATC was scheduled for the end of September, but a mechanical failure on the airship resulted in the postponement of this test. Equipment testing was conducted and the previous difficulties resolved. A new date was set after the airship was repaired; however, this date fell victim to the poor weather in the Northeast (the test must be conducted under Visual Flight Rules).

Figure 21: Airship at Floyd Bennet Field in Brooklyn. FAA and Alion personnel observing in the foreground.

Figure 22: Airship over Floyd Bennet field in Bridgeport.

Figure 23: Airship over the ground reference station at Sikorski Field.

Conclusions / Future

In conclusion, it appears that our early indications of altitude variations were correct. This is supported by research and predictions done in the 1970's and 1980's as well as by experiments and calculations of our own. Over the past couple of years our ability to measure ASFs has improved and the more recently measured data has the same differences with altitude that are predicted. However, in order to make accurate measurements to verify this effect, a stable platform that will allow for data averaging is needed. The testing with the airship will enable this to be done. Our predictions are also dependent upon the accuracy of the BALOR model for the ASF component of the predictions. Our work on validating BALOR and working with Ohio University to improve the performance of BALOR will enable us to make confident predictions of the altitude effect at the airports of interest. Depending upon the ASF variation at an airport and the Loran station geometry, adding an altitude correction may lead to the use of multiple sets of static ASFs for that airport. Once BALOR is validated, the predictions can be used to bound this problem though.

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Disclaimer and Note

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the U.S. Coast Guard, Federal Aviation Administration, or any agency of the U.S. Government.

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